How to Train Your Lander: Automatic moonquake detection using machine learning

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Premise:

- Planetary missions are fundamentally constrained by a lack of available data and telemetry requirements.
- Power efficiency typically decreases throughout the lifespan of the mission, putting data telemetry at risk.
- Missions are vying for time in NASA's Earth-based receivers. The Deep Space Network (DSN) currently operates 39 missions and will support more than 30 NASA missions in development. As the number of missions increases, data volume limitations become a science-impacting constraint.

Objective:

Is it possible to train a robotic lander to recognize the difference between data and noise and only send back relevant data?

Advantage:

Decreased data volume could allow higher quality recordings or even more sensors and experiments.

Algorithm Requirements:

1. **Lightweight:** Both in power and computation
2. **General Detector:** No prior data will likely be available
3. **Adaptive:** As data comes in, the algorithm should be improved

Analog Experiment:

Can we build a seismic detector using Earth data and use it to detect moonquakes?
- Is there an opportunity to improve the existing seismic catalogs?

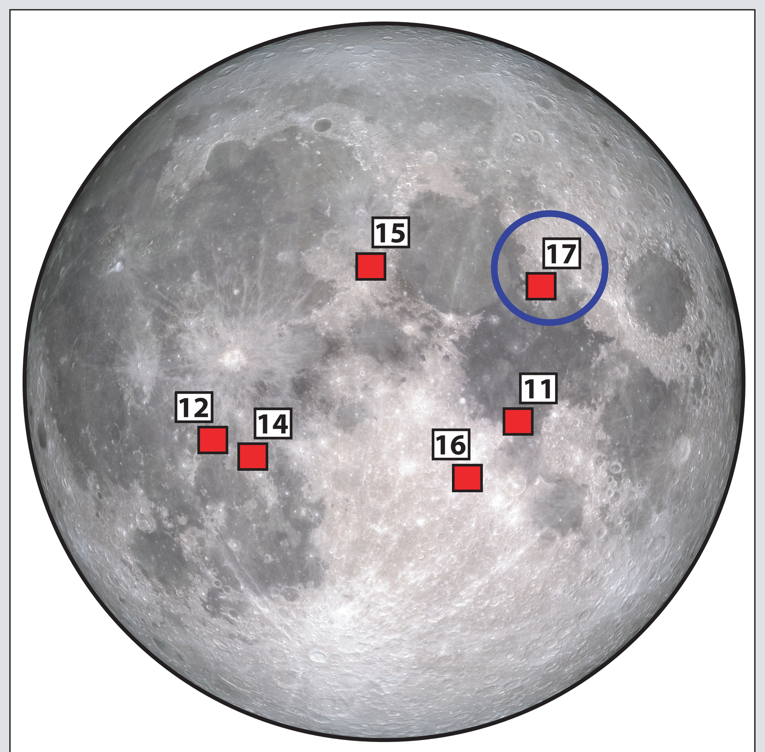


Figure 1:
Moon nearside with the location of each Apollo landing site as a red square. The Lunar Seismic Profiling Experiment (LSPE) was part of Apollo 17 (circled).

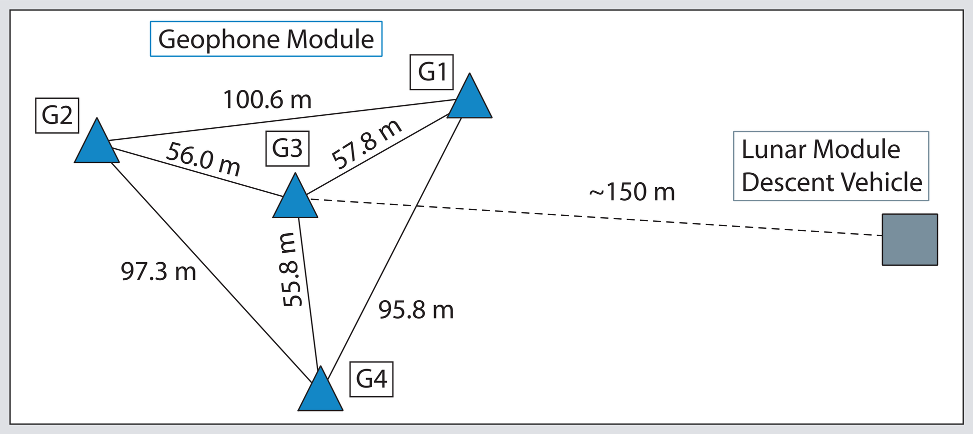


Figure 2:
Schematic of the LSPE geophone module and nearby lunar module descent vehicle [Heffels et al., 2017; Haase et al., 2019].

Background:

- Two seismic networks were installed during the Apollo missions: The **Passive Seismic Experiment (PSE)** for Apollo 11, 12, 14, 15, and 16, and the **Lunar Seismic Profiling Experiment (LSPE)** for Apollo 17 [Figure 1].
- PSE: 3-axis long-period (LP) instrument with 0.45 Hz center frequency. Over 13,000 events have been cataloged [Simmon et al., 1970 ; Lognonné et al. 2005].
- LSPE: Four geophones with ~117 Hz sample-rate. No systematic catalogs due to poor data quality [Kovach and Watkins, 1973, Figure 2].

Moonquakes:

- Impacts from meteoroids [Oberst & Nakamura, 1987].
- Deep quakes (between 700 - 1200 km) due to tidal stresses [Nakamura 2005].
- High-frequency shallow quakes (<200 km) produced by fault systems near deep impact basins [Watters et al., 2019].
- Rock fracturing due to thermal stresses induced by solar illumination (thermal moonquakes) [Duennebier & Sutton, 1974].

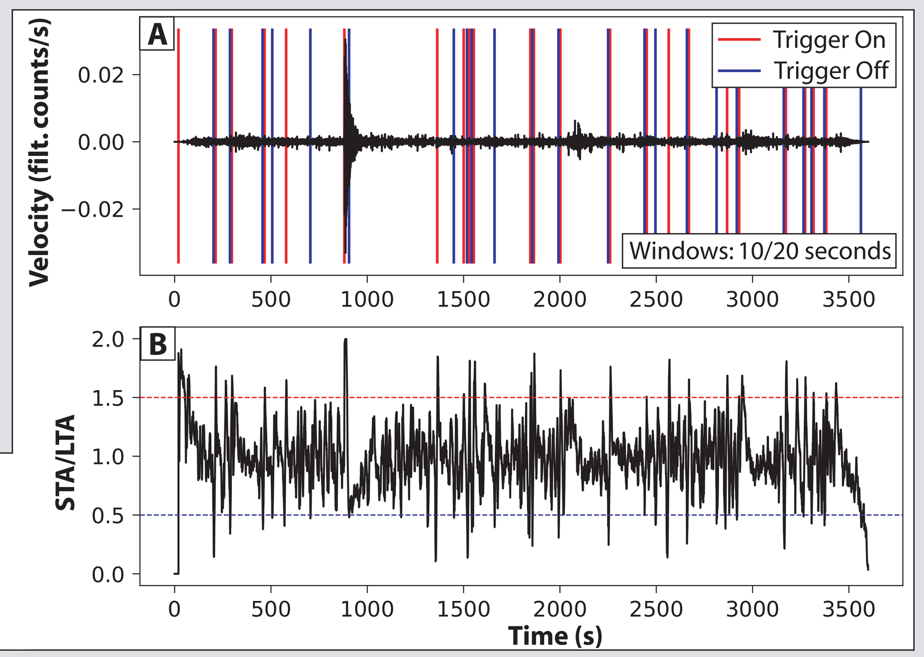


Figure 3:
Short-Term-Average/Long-Term-Average (STA/LTA) detections (a) and values (b) for 1 hr of LSPE seismic data using a trigger on of 1.5 (red lines), a trigger off of 0.5 (blue lines) and windows of 10 and 20 s.

Methodology:

1. 716 total events from a California seismic station were used for training: 134 of these in the validation set (~19%).
2. Twenty, twenty-second windows around "noise" and "earth quake" part of the spectrogram were used.
3. 2-5 layer Convolutional Neural Network (CNN) models were developed using *fastai* [Howard et al., 2018]. Spectrogram accuracy for each model was over 99%.
4. Models are tested on the cataloged Apollo PSE moonquakes and obtained 92-98% accuracy on Grade-A events.
5. The highest scoring model (MoonNet 3L) was applied to the Apollo LSPE.

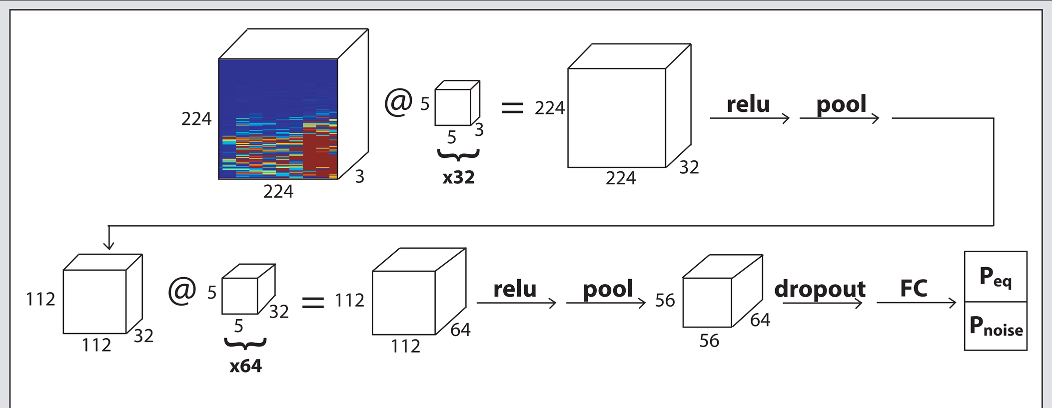


Figure 4:
Architecture for the 2-layer CNN used in this study.

For further information on the method please refer to:
Civilini et al., Geophysical Journal International, 2021

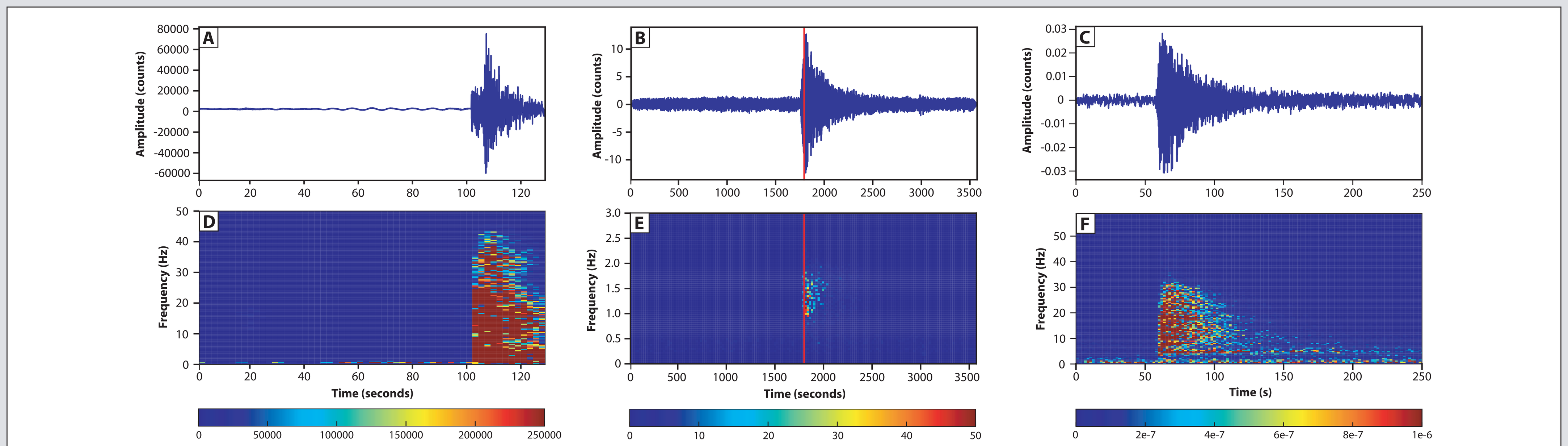
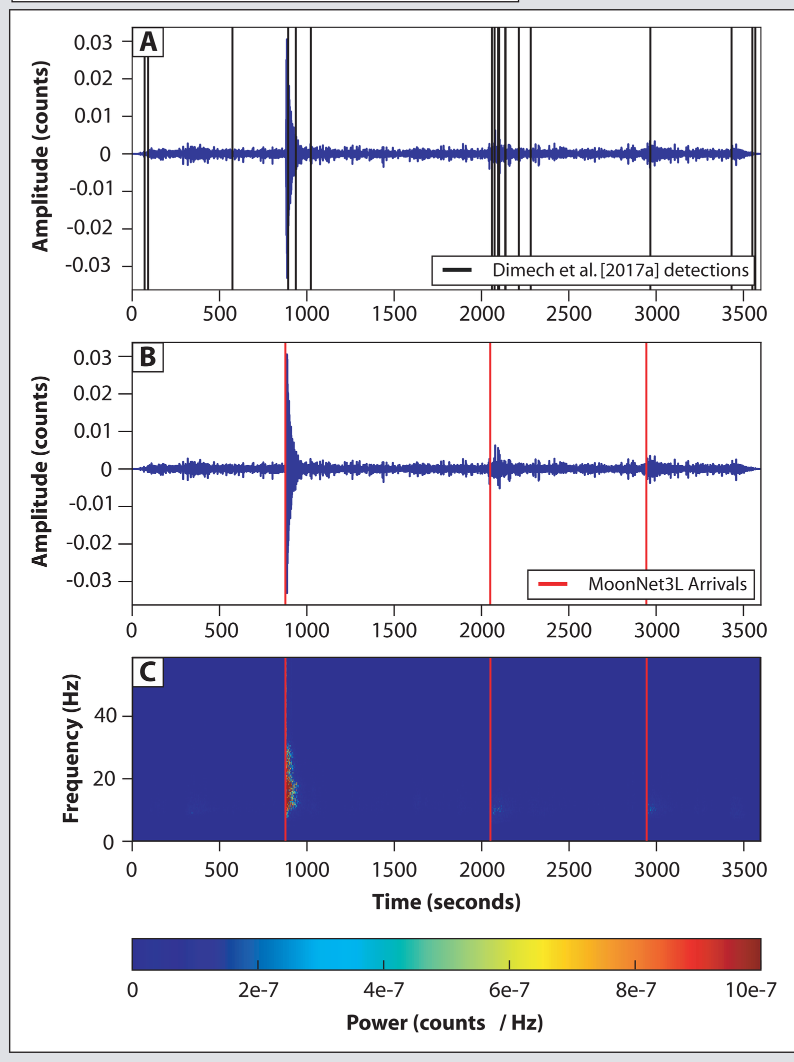


Figure 5:
Seismic traces of (a) a magnitude 3.7 earthquake recorded at the Pinon Flats Observatory station in California, (b) an impact moonquake from PSE Apollo 12 with the event arrival time from Nakamura et al. (1981) marked as a vertical line and (c) a thermal moonquake recorded at Geophone 1 during the LSPE. Spectrograms of each event are displayed in (d), (e) and (f).

LSPE Detection Results:



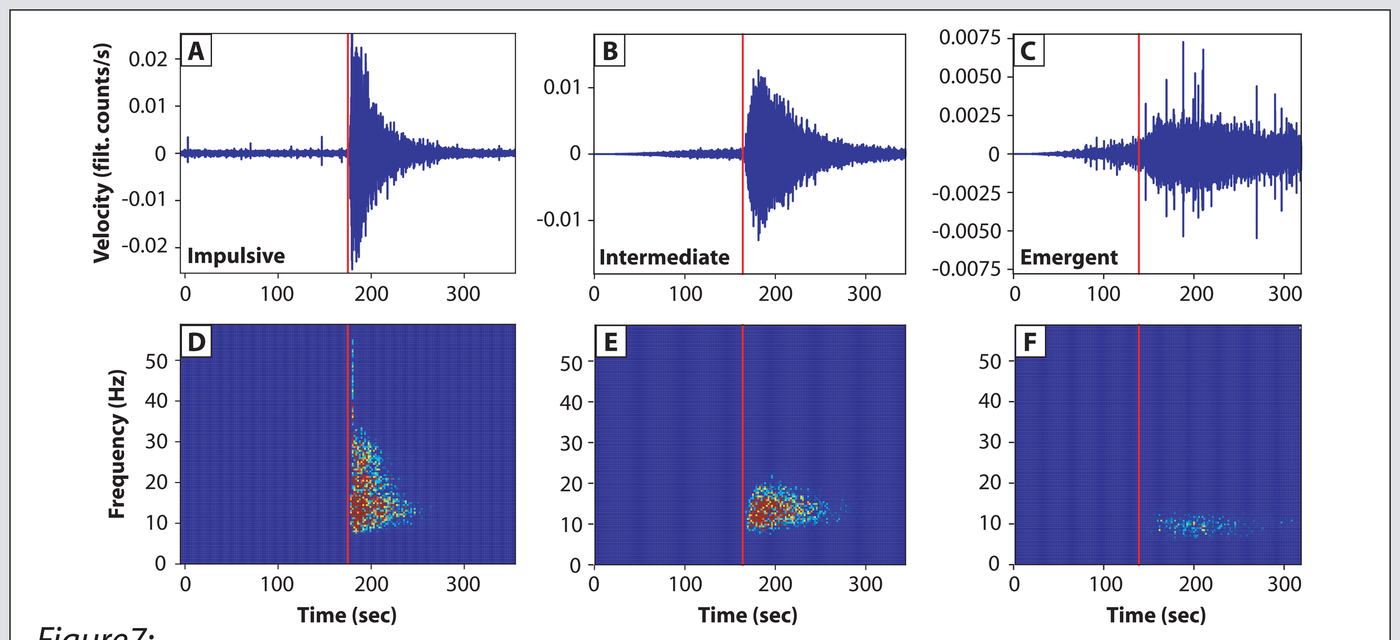


Figure7:
Thermal events are usually catagorized by risetime class or emergence: [A, D] Impulsive event, [B, E] intermediate event, and [C, F] emergent event.

Figure 6:
Example of seismic detections on a one hour segment of seismic data from the LSPE. [A] Detections by Dimech et al. [2017] (black lines) using hidden Markov Models and a lunar training set, [B] detections by Civilini et al. [2021] (red lines) using CNNs trained on Earth spectrograms, [C] spectrogram of time-series data.

Waveform Parameter Assessment:

Emergence (rise time) and **fine-tuned arrival**:
Frequency-based algorithm using gradients

Peak-ground-velocity (PGV):
Removed the effects of AD converter and compressor.

Incidence azimuth:
Iterating travel-time misfit equation using stochastic gradient descent.

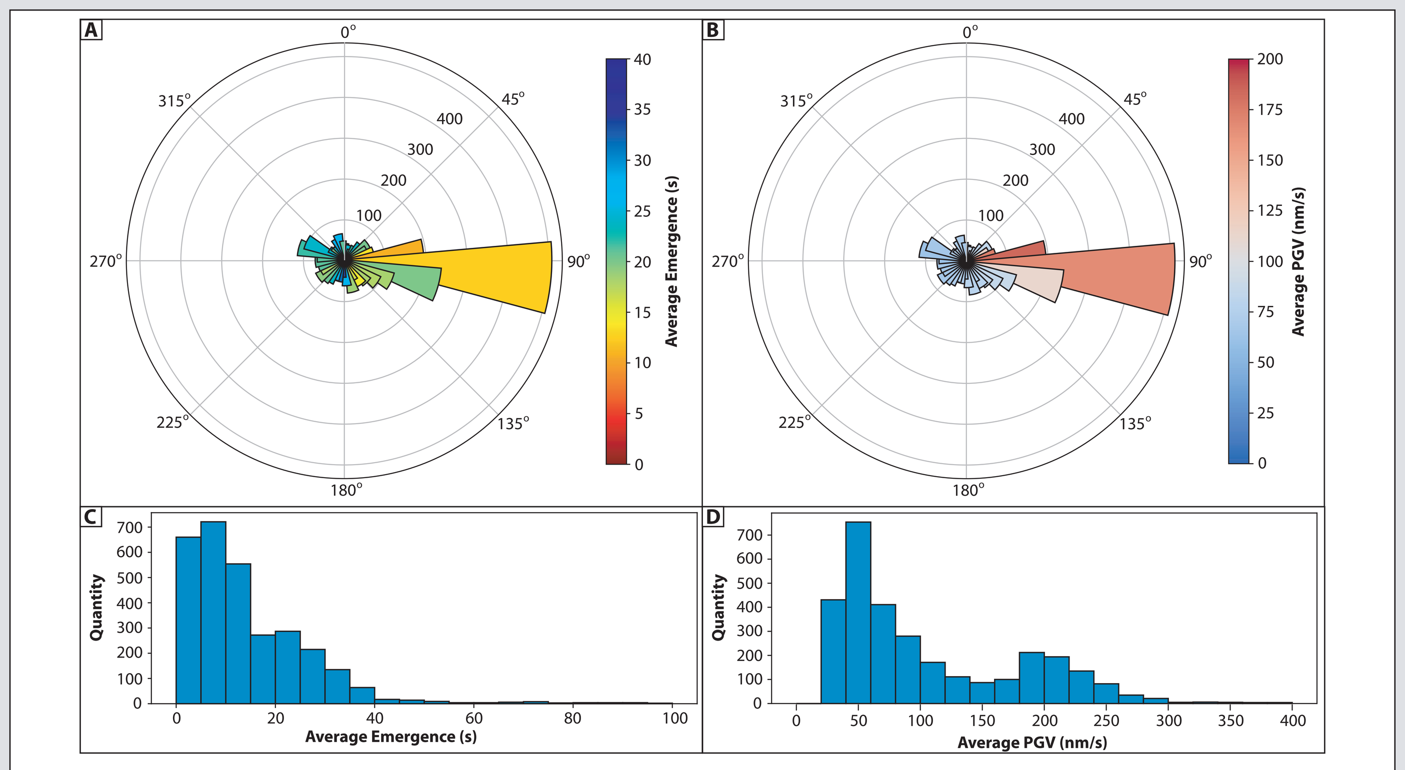
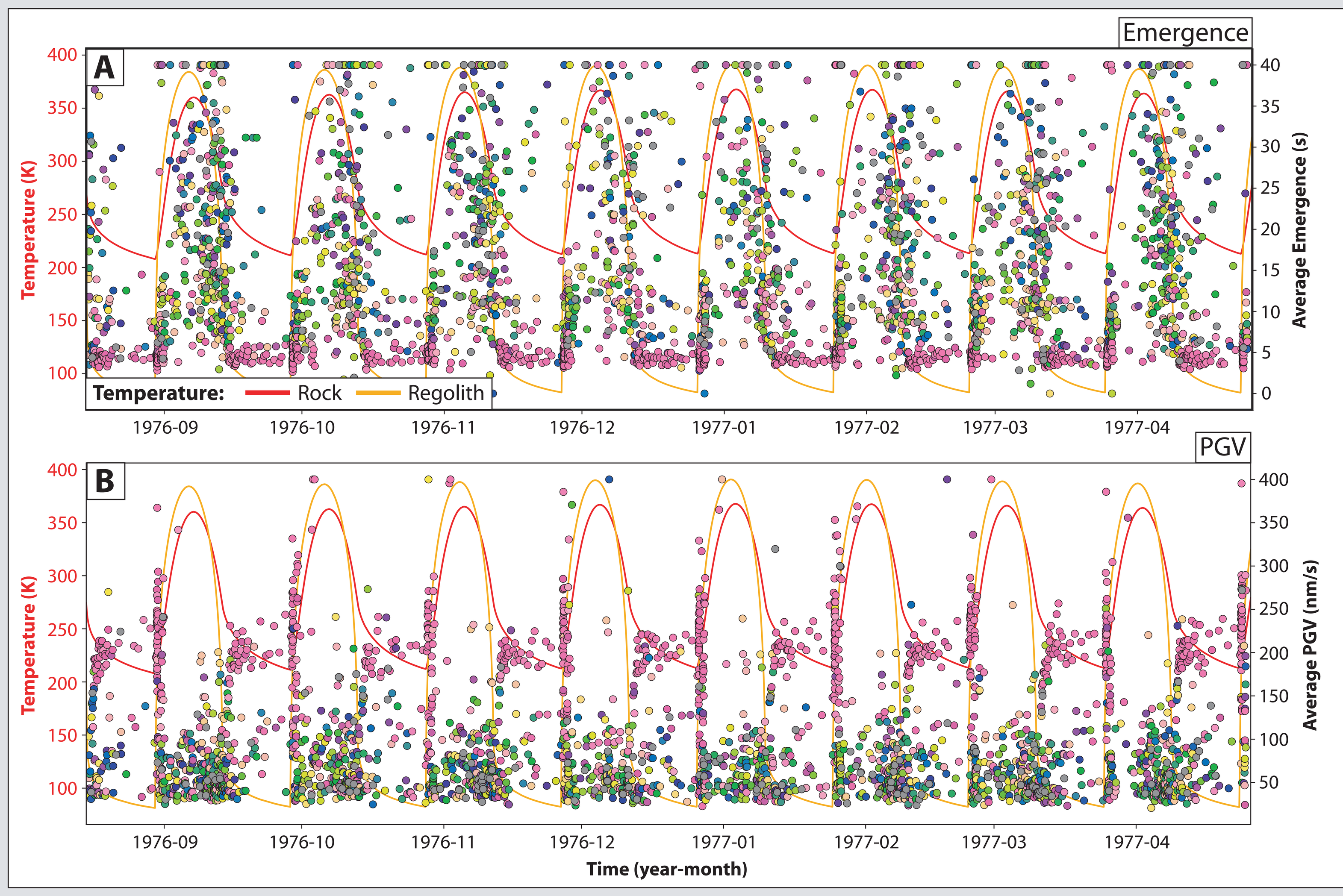


Figure 8:
Moonquake azimuth rose plots color-scaled by average emergence [A] and peak-ground-velocity (PGV) [B]. Histograms of moonquakes using average emergence [C] and PGV [D]. The impulsive, high-PGV events to the east of the array are produced by the LM.



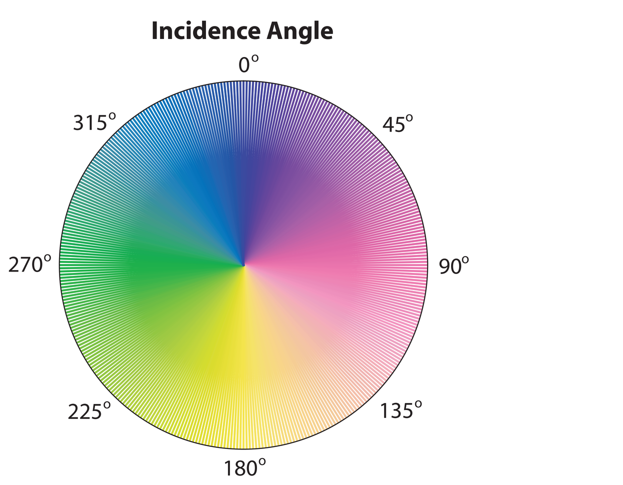


Figure 9:
[A] Moonquake distribution in time scaled according to average emergence. [B] Moonquake distribution of subplot A scaled according to average peak-ground velocity. For each plot, temperature distributions of the rock and regolith are displayed as red and orange curves respectively, and scatter points are colored according to incident azimuth.

Key points:

1. We determined the first systematic catalog of thermal moonquakes within the LSPE using a small amount of earthquake training data. This demonstrates that lander-side decision making is possible with simple algorithms even without a local training set.
2. Two moonquake distributions are observed: Impulsive events caused by the lunar module descent vehicle and emergent events driven by natural regolith surface processes.
3. Moonquake emergence (rise-time) is correlated with temperature, suggesting that scattering changes during the day-night cycle.

Upcoming work:

- What is the mechanism driving the scattering changes in the lunar regolith? We will develop new algorithms to improve the catalog and locate the events.
- Why does the lunar module vibrate, considering that the astronauts left almost 5 years prior? How does this effect upcoming and proposed lunar seismological missions (e.g. Farside Seismic Suite, Lunar Geophysical Network, etc.)?
- How does the methodology and code work in real-time? We will use an upcoming mission to test the true accuracy of the code.

- *Civilini et al., GJI, 2021*
- *Civilini et al., JGR: Planets, In Revision*
- *Dimech et al., Results in Physics, 2017*
- *Duennebier & Sutton, JGR, 1974*
- *Howard et al., fastai, 2018*
- *Kovach and Watkins, Science, 1973*
- *Lognonné, Annu. Rev. Earth Planet. Sci., 2005*
- *Nakamura, JGR, 2005*
- *Oberst & Nakamura, JGR: Solid Earth, 1987*
- *Simmon et al., Apollo 12 PSR, 1970*
- *Watters et al., Nature Geoscience, 2019*